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Inventory and comparative characteristics of dryers used in the sub-Saharan zone: Criteria influencing dryer choice

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ABSTRACT

A survey was carried out in Togo, Benin and Burkina Faso involving 140 respondents and three climatic zones. Ten typical types of dryers with batch operating and natural convection were inventoried. Analysis of the results showed that: (1) Traditional sun dryers were widely used everywhere from 1 to 4000 kg per cycle, costing €0 to €7.63 per m^2 drying area. (2) Low power solar dryers were mostly used in the Sahel and Sudan-Sahel tropical climate, from 5 to 1000 kg, costing from €9.11 to €238.55 per m^2 of tray. (3) Gas dryers were used in all climatic zones at around 100 kg per cycle, with a high drying power, costing from €107.52 to €181.75 per m^2 of tray. The acquisition of dryers depended mostly on the distance between provider and user and on the means of dissemination.

A thermo-economic analysis was carried out to determine which dryers were most successfully adopted. These dryers will be re-employed by the users when the investment and maintenance costs enable profit to be made from the drying operation. Two types of dryers met those conditions: the traditional simple sun dryer used by families and groups: a study of an application on maize showed costs of €0.01/kg of evaporated water equal to 7% of daily capital gain; the Atesta gas dryer used by small and medium-sized enterprises: applied to pineapple, cost €0.07/kg of evaporated water equal to 9% of daily capital gain. New criteria had to be added to all those listed from the literature in order to choose a dryer properly: characteristics of the product to be dried, product added value, local energy availability and cost, labour skills and availability, local material availability and user investment capacity.

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1. Introduction

Drying is a significant activity in the food production chain. Drying processes are far less advanced in developing countries than in western countries. They are often used for food preservation to avoid product losses [1]. Many food products are dried in rural and urban areas for both local consumption and export [2].

Over the past 30 years, many studies have been carried out on tropical food drying and dryers for and in developing countries (Asia, Africa or South America) [2,3]. Many of those studies focused on improving the dryer thermal efficiency and less on the product quality. Very few were concerned with technology innovation dedicated to decreasing the costs of drying [4–9]. It is important to note that: most food products are still exposed to the sun for natural solar drying (sun drying) and most dryers developed either by academics or manufacturers meet low commercial success.

The literature on the classification of dryers, on an industrial scale, is abundant [10–12]. On a craft scale and for agricultural applications, Ekechukwu and Norton [13], Murphy [14], Sharma et al. [2] and Fudholi et al. [6] proposed recent reviews on classifications of solar dryers mainly based on scientific literature.

The choice or the design of a dryer adapted to a specific need remains a major issue [10,15]. According to a survey involving 14 European Chemical Companies [10], "over ninety percent of the companies had made errors in the selection of their new dryers". In the literature, the dryer specification criteria are different from one author to another, which makes it difficult to compare them [14,16]. Most studies and reviews on food product dryers do not mention the areas or countries surveyed. In a developing country context, Marouzé and Giroux [17], Desmorieux and Idriss [18] showed from field studies that most food processing equipment, including dryers, does not integrate a preliminary study of user requirements. For those authors and for Mujumdar [10], a more appropriate dryer selection involves the identification of the dryer user's needs together with the characterization of the existing dryers. Consequently, choosing a dryer should take into account the user needs as well as the end use of the dried product, which are two criteria rarely mentioned in existing scientific literature. To that end, in order to more effectively reflect reality in the field, this work was positioned at the interface among several domains: the technical efficiency of dryers, process engineering and socio-economic reality.

This article reports on and analyses the results of a survey on drying equipment for small- and medium-scale use in three West African countries, Togo, Benin and Burkina-Faso.

Initially, to characterize and class the dryers listed, a review of the literature was undertaken to gather all the criteria considered to qualify dryers. They were numerous and varied depending on the studies reviewed. They can be grouped into five classes: specifications of the dryers, specifications of the products, energy and mass balance aspects, specifications of the environment including the users and economic aspects. The survey revealed that not all the criteria were sufficient for taking into account the environmental context or for understanding why energy-efficient dryers, according to the literature, were not adopted in the field. The study therefore proposes some new criteria.

Not all the criteria from the literature could be used to describe the dryers listed, because the existing criteria were not all adapted to the developing countries situations in our study. The dryers listed are all classed into 10 typical types, they were characterized with the data collected from the survey, some criteria from the

Nomenclature

$C_{dry,d}$	drying cost per day (€/d)
$C_{dry,w}$	drying cost per kg of evaporated water (€/kg)
C_{elec}	electricity kW h cost (€/kW h)
C_{enrg}	dryer energy consumption cost per day (€/d)
CG_d	daily capital gain (€/d)
C_{maint}	dryer annual maintenance cost (€/year)
$C_{\%dry}$	part of drying cost in the daily capital gain (%)
E	total energy received per day by the dryer (kJ/d)
E_g	energy from gas combustion per day (kJ/d)
E_s	solar energy collected by the dryer per day (kJ/d)
E_v	daily energy to evaporate water from product (kJ/d)
I	solar irradiation (kJ/m^2 d)
ICP	inferior calorific power (kJ/kg)
L_v	vaporization water latent heat (kJ/kg)
$m_{f,cy}$	final mass of dried product per cycle (kg/cycle)
$m_{g,cy}$	gas mass per cycle (kg/cy)
$m_{g,h}$	gas mass per hour (kg/h)
$m_{i,cy}$	initial mass of humid product per cycle (kg/cycle)
$m_{i,d}$	initial product mass flow (kg/d)
m_{i,d_s}	initial product flow per m^2 of collector (kg/d m^2)
m_{i,d_t}	initial product mass flow per m^2 of tray (kg/d)
$m_{RM,cy}$	raw material mass per cycle (kg/cycle)
M_w	evaporated water mass flow from the product (kg/d)
$N_{d/y}$	number of days' dryer operation per year (d/year)
P_{DP}	price of dried product per kg (€/kg)
P_{dryer}	purchase price of the dryer (€)
$P_{dryer,p}$	dryer purchase price per product mass flow (€ d/kg)
$P_{dryer,w}$	dryer purchase price per water flow (€ d/kg)
P_{RM}	price of raw material per kg (€/kg)
Pt_w	profit per evaporated water mass flow (€/kg)
S_{dir}	projected tray area perpendicular to solar radiation reaching the products (m^2)
S_{ind}	projected collector area perpendicular to solar radiation (m^2)
S_t	total tray area (m^2)
TO_d	daily turn-over (€/d)
X_f	final moisture content of product (dry basis) (%)
X_i	initial moisture content of product (dry basis) (%)

Greek letters

Δt_{cy}	duration of the drying cycle (d)
Δt_{fan}	fan use time per day (h/d)
Δt_g	gas use time per day (h/d)
Δt_{life}	life span (year)
ε	dryer efficiency (%)

Subscripts

a	ambient
cy	cycle
D	dryer
d	day
dir	direct
dm	dry matter
DP	dried product
dry	drying
$enrg$	energy
$elec$	electricity
f	final
fan	fan
g	gas
h	hour
i	initial
ind	indirect
m	month
$maint$	maintenance
o	outlet
p	per kg of product mass flow
RM	raw material
s	solar or per m^2 of collector area
t	tray or per m^2 of tray area
V	vaporization
w	water or per kg of water mass flow
y	year

literature and some newly proposed. Following a technical description, the dryers listed are characterized by:

– technological aspects (capacity, material, etc.),
– operational aspects (products, end use, drying time, maximum temperatures used, etc.),
– the mean mass flow values,
– costs,
– the characteristics of the products to be dried,
– the kinds of users.

The products were all physically characterized by geometric parameters, such as the maximum drying air temperature, initial and final moisture content. The drying activity was qualified and the dryers used were classed by taking into account the social, technical and economic aspects. Also in this paper, criteria are proposed for calculating drying costs, investment costs and energy consumption profiles, making it possible to characterize the performance and profitability of the dryers for the users. All these criteria complete the list obtained from the analysis of the literature review.

The comparison of dryers in the literature is usually carried out by looking at the drying rates of a given product with various drying modes [19], which could not be done in our context, due to the different places, climates and dried products involved in the field. Some other new criteria were therefore proposed for a social/thermal/economic evaluation, which are presented in this paper. The values of these new criteria were calculated for six of the dryers listed, with the data collected in a real drying situation on the spot. The analysis and comparison of the criteria values provided a clearer picture of the situation in the field, helping to explain the adoption, or not, of several dryers.

Thanks to those calculations, and taking into account the identified criteria, the most efficient dryers were determined. This study enabled a classification and an analysis of necessary and relevant criteria. This will be useful for choosing or designing dryers for user-specific needs.

2. Materials and methods

2.1. Selection of classic criteria for dryer characterization and evaluation

Numerous criteria are used to class and evaluate dryers. These criteria differ from one author to another. Augustus Leon's [16] observations show that there are more than one standard

Table 1
Dryer classification criteria and their characteristics.

Criteria	Dryer characteristics	Examples of dryers	References
Type	Industrial	Fluidized bed dryer, freeze dryer	[11]
	Small-scale	Sun drying, Hohenheim, Atesta, shell dryer	[2,13]
Energy	Fossil fuel or electric	Atesta, fluidized bed dryer	[20,21]
	Solar	Hohenheim, greenhouse	[22,23]
	Hybrid (solar + fossil or electric)	Geho dryer	[24]
Solar energy collection	Direct	Cabinet dryer, greenhouse	[23,25]
	Indirect	Shell dryer	[26]
	Mixed	Hohenheim, chamber dryer	[22,27]
Physical state of products	Solid	Rotary dryer	[20]
	Paste	Drum dryer	
	Liquid	Spray dryer	
Operation mode	Batch	Tray dryer, MO5, cupboard	[10,13,20]
	Continuous	Spray dryer	
Drying time	Ultra short (< 1 min)	Spray dryer	[10,20]
	Short (from 1 min to 60 min)	Fluidized bed dryer, rotary dryer	
	Long (> 60 min)	Tunnel dryer, greenhouse, silo	
Product movement	Stationary	Cupboard dryer	[10,12–14]
	Moving	Fluidized bed dryer, rotary	
	Stirred or dispersed	Fluidized bed dryer, vibrated bed dryer	
Number of stages	Single	Tray dryer	[10]
	Multi-stage	Fluidized bed dryer	
Drying temperature	Above boiling temperature	Drum dryer, rotary dryer	[10,20,28]
	Below boiling temperature	Greenhouse, cupboard	
Operating pressure	Above atmospheric pressure	Dryer pneumatic	[10,20]
	Below atmospheric pressure	Drum dryer	
	Vacuum	Vacuum tray dryer	
Drying medium	Air	MO5, Atesta, cupboard	[10,11,29–31]
	Superheated steam	Fluidized bed dryer	
	Flue gases	Rotary dryer	
Heat input type	Convection	Tunnel dryer, fluidized bed dryer	[10,11,20]
	Conduction	Indirect rotary dryer, drum dryer	
	Radiation	Fluidized bed dryer, solar, microwave	
	Combination of different modes	Mixed solar dryer	
	Continuous or intermittent	Solar/electric dryer	
	Adiabatic or non-adiabatic		
Ventilation	Passive dryer	Atesta, greenhouse dryer	[32]
	Active dryer	Geho dryer, spray dryer	[11,28,33]
Relative air-product flow type	Co-current (parallel flow)	Tray dryer	[10,34]
	Counter-current (parallel flow)	Tray dryer	
	Cross flow (traversing air flow)	Fluidized bed dryer	
	Mixed-flow (parallel and traversing air flow)	Spray dryer, rotary dryer	[35]

Table 2
Dryer quantitative and evaluation criteria.

Criteria	Details	References
Dryer specifications	Dryer type (Table 1)	[36,37]
	Dryer sizes	[38]
	Power installed: gas burner, electric resistance or solar collector area	[25,39]
	Dryer capacity	[33]
	Number of trays, tray area	[16,40]
	Ease of loading and unloading	[41]
	Ease of handling, cleaning and maintenance	[41]
Product specifications	Sensorial qualities : taste, texture, aroma, colour	[42]
	Nutritional qualities	[43-46]
	Rehydration capacity	[47]
	Drying uniformity	[21]
Energy and mass transfer performance	Daily evaporator capacity	[48]
	Drying time	[49]
	Dryer thermal efficiency	[50]
	First day drying efficiency	[51]
	Drying air temperature	[52,53]
	Drying air relative humidity	[52,53]
	Maximum air temperature	[27]
	Time for $(T_s - T_a) > 10$ °C	[14]
	Drying air flow rate	[54]
Environmental specifications	Floor space requirement	[55]
	Skilled technician and operator requirement	[41]
	Safety conditions	[21]
Economic characteristics	Dryer and drying cost	[55-57]
	Payback period	[27,55,58]

Table 3
Criteria used in this study.

Information type	Criteria from literature	New criteria	Calculated criteria
Dryer specifications	Dryer type Energy type Sketch of the dryer showing operating Principles description Photo Energy used Ventilation Relative tray positions Tray area Air flow type in the dryer Operation mode Relative air–product flow Drying time Dryer capacity (in fresh product) Dryer life time	Number or trays Main materials used Average number of dryer use days per year	Drying area Wet product mass per tray
Product specifications	Product name/product category Initial moisture content Final moisture content Presentation form of fresh product Maximum temperature for product drying	Other products dried in the same dryer Mean sugar content	Dried product mass per cycle
Energy and mass balance	Solar radiation Heat input Other energy characteristics Collector area Collector efficiency Mean drying air temperature Mean drying air relative humidity		Effective used energy per day Drying efficiency Evaporated water mass per day
Environmental specifications	Climatic zone Mean ambient air temperature Mean ambient air relative humidity	Dryer advantages and drawbacks as perceived by the users Land space availability User types Users' organisation level Geographical zone Energy cost and availability	
Economic characteristics	Raw material cost per day Dried product cost Dryer cost Operating cost Most "fragile" part of dryer Capital gain Turn-over per day Payback period of the dryer	Investment capacity (costs for users of the dryer) Outlet market for the dried product	Drying cost Maintenance cost Part of drying cost in turn-over Capital gain Share of profit in capital gain

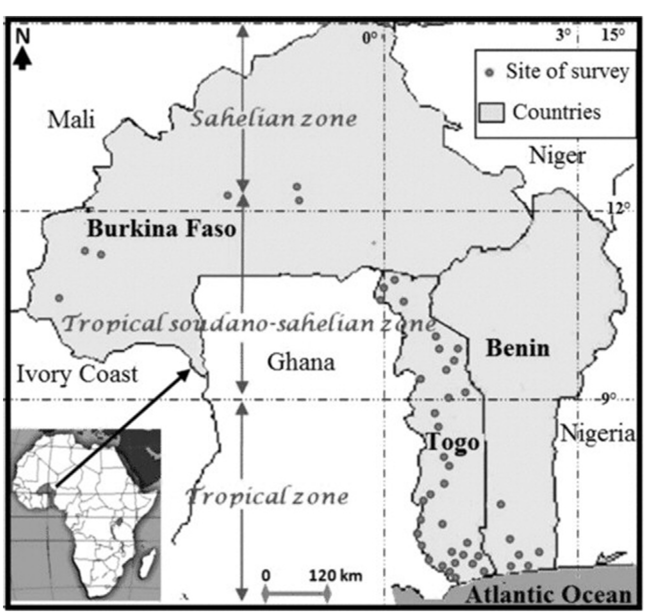


Fig. 1. Sites of the survey in Togo, Benin and Burkina Faso.

procedure: for example, the one proposed by the National Office of Standards of the American Society of Heating, Refrigeration and Air Conditioning Engineers noticeably differs from that of Bundesverband Solarenergie in Germany.

In this study, the criteria selected from the literature used for dryer specifications have been grouped in Tables 1 and 2. Qualitative criteria (Table 1) enabled us to define the types of dryers and to class them. The quantitative criteria in Table 2 were used to compare data (physical or chemical properties, drying and dryer specifications, product quality and value, etc.) and assess their performance (thermal efficiency, energy and mass balance, etc.).

The survey was undertaken on the basis of the criteria in Tables 1 and 2. New criteria were added so as to better characterize the drying context specific to the sub-Saharan zone. Some criteria and parameters were not considered due to the impossibility of assessing their values during the survey, such as rehydration and nutritional quality analyses of the dry products. The criteria ultimately adopted are listed in Table 3. The quantitative criteria in Tables 2 and 3 are grouped according to five types:

- Dryer specifications.
- Fresh and dried product specifications.
- Energy and mass balance.

- Environmental specifications.
- Economic characteristics.

The qualitative and quantitative criteria were closely connected. Most studies refer either to industrial or small-scale production dryers (first qualitative criterion Table 1) and are shared with quantitative criteria (Table 2). For industrial dryers, product flows from some hundred kg/h to several t/h were used, with a drying time of less than a few hours [20]. They use fossil energy or electricity. In that study, only small-scale dryers were taken into account: their evaporating capacity was of a few kg of water per hour; their drying time often lasted several days and they mainly used renewable energies (biomass, solar energy) [4,16]. Hybrid systems combining solar and fossil energy were also sometimes used.

The classification proposed is according to the criteria in Table 3. Dryers using solar energy are ordered and named according to the definition of the majority of authors [2,6,13,14,21–23]:

(1) Sun dryers which are traditional devices where solar radiation directly warms the products which are often not protected against insects, dust and rain.
(2) Direct solar dryers: dryers where solar radiation directly warms the products through a transparent cover.
(3) Indirect solar dryers: the drying air is heated by solar radiation through a collector, and then it transfers its energy to the product.
(4) Mixed dryers: products are exposed to the sun and receive hot air from a solar collector.
(5) Hybrid dryers: sun or solar dryers which are able to receive, in addition, another form of energy.

2.2. Survey conditions

The survey work was carried out in three countries of West Africa: mainly in Togo, and extended to Benin and Burkina Faso (Fig. 1). That geographical area covered three different climatic zones: (1) the wet tropical zone between the 6th and 9th northern parallel, (2) the Sudan-Sahelian tropical zone between the 9th and 12th northern parallel and (3) the Sahelian zone from the 12th northern parallel. Similar climatic conditions can be found on other continents (Africa, Asia and South America) with similar drying issues.

The population targeted was dryer users and manufacturers. In this survey, we considered the drying of agricultural products on a small scale, where drying was the main or only process. Industrial drying was not taken into account, such as drying of pharmaceutical products, mineral products such as clay or phosphate, or drying of meat and fish products.

In Togo, the survey was conducted in 37 locations spread over the five economic regions of the country. Six localities in the south of Benin and six towns in central and south-western Burkina Faso were also visited (Fig. 1). The study took into account 123 respondents in Togo, 7 in Benin and 10 in Burkina Faso.

The goals of the survey were to:

- make an inventory of the dryers in operation, including traditional ones.
- characterize the dryers studied, based on the criteria described in Table 3.
- class the dryers according to the most important criteria.
- and determine the dryers that were thermally and economically efficient.

Qualitative and quantitative data were collected in the survey from written questions in the form of an exploratory and descriptive interview guide [59].

2.3. Drying and investment cost

Considering that the product mass to be dried can be lower than the initial product mass due to a possible withdrawal of the stone and/or the skin, we distinguish the raw material mass per cycle $m_{RM,cy}$ from the initial mass of humid product mass per cycle $m_{i,cy}$. The initial product mass flows $m_{i,d}$ (kg/d) are expressed by Eq. (1).

$$m_{i,d} = m_{i,cy}/\Delta t_{cy} \tag{1}$$

where $m_{i,cy}$ is the capacity of the dryers (the initial fresh product mass), and Δt_{cy} is the duration of the drying cycle (expressed in days). To compare the various dryers, these mass flows are reported to the unit of tray area S_t which gives m_{i,d_t} according to Eq. (2).

However, owing to the fact that certain dryers can be undersized compared to the load of product treated, for solar dryers, the mass flows of the product $m_{i,d}$ are also reported in relation to the solar collector area obtaining m_{i,d_s} in Eq. (3). For the gas dryers, the product mass flows (kg/d) are given by considering the gas consumption flow. In order to take into account the orientation of the solar collectors, the areas considered are those projected from the direct S_{dir} and indirect S_{ind} collector area orthogonally to the solar radiation.

$$m_{i,d\_t} = m_{i,d}/S_t \tag{2}$$

$$m_{i,d\_s} = m_{i,d}/(S_{dir} + S_{ind}) \tag{3}$$

The purchase price of the dryer P_{dryer} (€) was reported to the initial product mass flow, to enable a comparison of the investments for the various dryers. The dryer purchase price per product mass flow $P_{dryer,p}$ is given by Eq. (4).

$$P_{dryer,p} = P_{dryer}/m_{i,d} \tag{4}$$

2.4. Thermo-economic characterization of the inventoried dryers

The information collected in the investigations was supplemented by evaluating the energy and economic performance of six dryers which were regarded as characteristic of the inventoried dryers. This was done through an evaluation of the energy efficiency of the dryer, the cost of drying per kg of evaporated water and profit achieved. The calculation procedures are described below.

2.4.1. Available energy

The energy was supplied by solar, gas or electricity.

The solar radiation at the surveyed sites that we used was the total radiation measured by three recording stations: in Lomé (Southern), in Atakpamé (Centre) and Mango (Northern) and exploited by the UNESCO Chair on Renewable Energies, at the University of Lomé [60,61]. For each surveyed site, the sunshine data I (kJ/m^2 d) considered were those at the nearest recording station. Calculated from the areas that depended on their orientation, the solar energy received per day E_s (kJ/d) by the dryer is given by the addition of the projected tray area S_{dir} perpendicular to solar radiation reaching the products and the projected collector area S_{ind} perpendicular to solar radiation by Eq. (5):

$$E_s = I(S_{dir} + S_{ind}) \tag{5}$$

The domestic gas used, in 12 or 25 kg cylinders, was generally propane. In this study we considered an ICP of 46,000 kJ/kg according to [62]. The daily energy E_g (kJ/d) supplied to the dryer by gas was calculated from the average gas mass used per cycle $m_{g,cy}$ indicated by the operators, considered in relation to the duration of the cycle Δt_{cy} according to Eq. (6):

$$E_g = (m_{g,cy}/\Delta t_{cy}) \times ICP \tag{6}$$

The only use of electricity noted at the time of the investigation was for fans. Due to the low level of power used, this was not taken into account in the heat balance, but its cost was considered in the economic calculations.

The energy provided to the dryer per day E (kJ/d) was given by the sum of solar energy collected E_s, and that resulting from domestic gas combustion E_g, defined by Eq. (7):

$$E = E_s + E_g \tag{7}$$

2.4.2. Energy efficiency

Energy efficiency is defined by the ratio of the energy E_v necessary to evaporate the water contained in the product by the energy E provided to the dryer.

The quantity of water evaporated throughout the drying cycle of a product is expressed by day of drying. The average water mass evaporated per day M_w (kg/d) was calculated by considering the initial X_i and final X_f moisture contents of the product (obtained from the literature), the duration Δt_{cy} of the drying cycle and the initial mass $m_{i,cy}$ of the fresh product according to Eq. (8):

$$M_w = (m_{i,cy}/\Delta t_{cy}) \times [(X_i - X_f)/(1 + X_i)] \tag{8}$$

The energy necessary E_v (kJ/d) to evaporate this daily evaporated water mass flow M_w (kg/d) was estimated by Eq. (9). The vaporization latent heat of water L_V corresponding to the operating temperature ranges is equal to 2250 kJ/kg [62]. The desorption energy was not considered:

$$E_v = M_w \times L_v \tag{9}$$

The energy efficiency ε of the dryer did not just qualify the dryer but the dryer/product pair, and was given by Eq. (10):

$$\varepsilon = E_v/E \tag{10}$$

2.4.3. Drying cost and profitability

From an economic viewpoint, the costs were evaluated from the data collected for the six dryers analyzed. The cost of daily energy consumption C_{enrg} (€/d) was a total of the cost of daily gas consumption plus electricity for each dryer start-up. This consumption was calculated according to the use period for the gas Δt_g and for the fan Δt_{fan} as shown in Eq. (11):

$$C_{enrg} = P_g \times m_{g,h} \times \Delta t_g + P_{elec} \times P_{fan} \times \Delta t_{fan} \tag{11}$$

where P_{fan} is the fan power. The prices of the gas P_g and electric kW h P_{elec} are those in use in Togo in 2010, € 0.43/kg and € 0.27/kW h, respectively. The daily drying cost $C_{dry,d}$ (€/d) took into account the dryer purchase price P_{dryer} (€), the annual maintenance cost C_{maint} (€/y), the daily energy consumption C_{enrg} (€/d), the life span of the dryer Δt_{life} (years) and the average number of days of dryer operation per year $N_{d/y}$, in Eq. (12):

$$C_{dry,d} = [(P_{dryer} + C_{maint} \times \Delta t_{life})/(\Delta t_{life} \times N_{d/y})] + C_{enrg} \tag{12}$$

The dryer purchase price P_{dryer} was provided by the users or by the manufacturers. The life span Δt_{life} of the dryers came from the literature [27–30], except for drying on a protective sheet (given by the users) and for the direct solar box (by the manufacturer). The annual cost of maintenance C_{maint} is obtained from the number of components to be repaired or replaced during the life span of the dryer (data provided by the users). The average number of days' use per year $N_{d/y}$ varied according to the users, depending on their drying activities.

The daily drying cost $C_{dry,d}$ was expressed in relation to the average water mass evaporated from the product per day M_w to obtain in Eq. (13) the cost of drying per kg of water evaporated for each dryer $C_{dry,w}$.

$$C_{dry,w} = C_{dry,d}/M_w \tag{13}$$

The daily turn-over per day (gross revenue) TO_d (€/d) and the capital gain (profit) of the drying activity per day CG_d (€/d) were evaluated from the dry product price per kg P_{DP}, the mass of dry product obtained per day $m_{f,cy}$, the price per kg of the raw material used P_{RM}, the raw material mass used per day $m_{RM,cy}$ and the duration Δt_{cy} of the drying cycle, with Eqs. (14) and (15), respectively. Raw material and dry product costs were collected at the local markets.

$$TO_d = m_{f,cy} \times P_{DP}/\Delta t_{cy} \tag{14}$$

$$CG_d = TO_d - m_{RM,cy} \times P_{RM}/\Delta t_{cy} \tag{15}$$

As the time taken for a return on investments could not be given because of a lack of complete data for all the costs of the drying units, the relative cost of drying $C_{\%dry}$ was considered in relation to the capital gain of the activity, through Eq. (16):

$$C_{\%dry} = C_{dry,d}/CG_d \tag{16}$$

The six dryers were classed by comparing their purchase costs in relation to water evaporative flow $P_{dryer,w}$ (€ d/kg) and the profit (excluding operating costs) considered in relation to the water evaporative flow Pt_w (€/kg), expressed by Eqs. (17) and (18), respectively:

$$P_{dryer,w} = P_{dryer}/M_w \tag{17}$$

Table 4
Traditional solar devices on the soil and on a support. (a) On a protective sheet. (b) On a sheet of steel. (c) On a roadside.

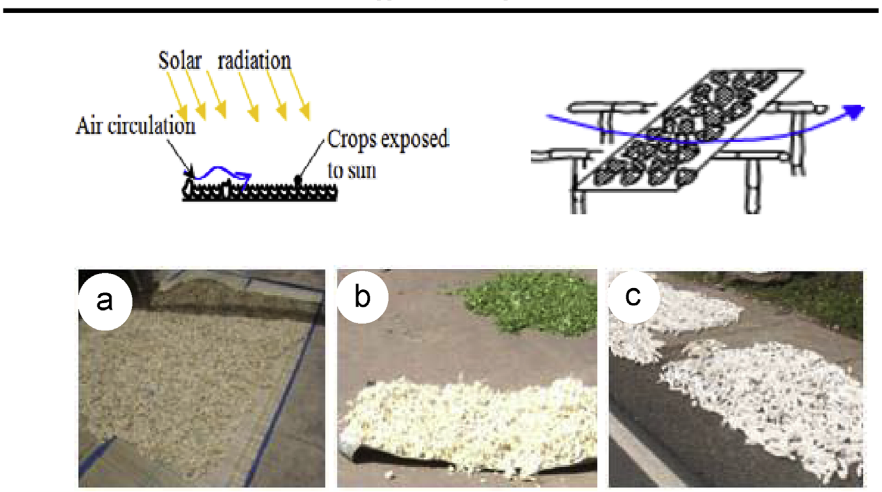
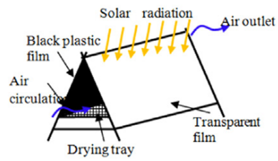


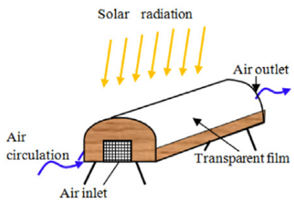
Table 5
Listed solar dryers.

Direct solar dryers

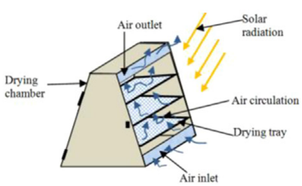
Tent



Greenhouse

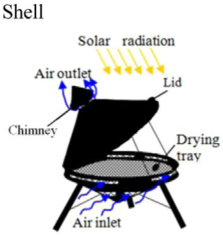


Direct cupboard

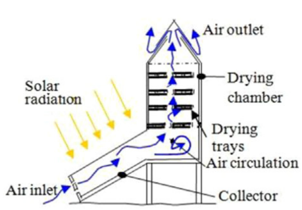


Indirect solar dryers

Shell

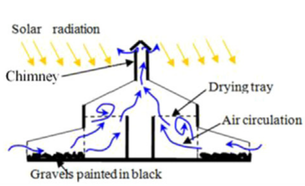


Indirect cupboard



Mixed solar dryer

Chamber



$$Pt_w = (CG_d - C_{dry})/M_w \tag{18}$$

3. Results and discussions

The review of inventoried dryer parameters (Section 2) shows a significant deficit in appropriate criteria for characterized dryers from the sub-Saharan zone. The most significant we propose for all inventoried dryer types include: the dried products used, the types of dryer users, the environmental specifications, the energy used, the drying specifications and the cost of the inventoried dryers.

The thermal and economic analyses of six characteristic dryers chosen from all the inventoried dryers follow.

3.1. *Inventoried dryer types*

Although there are many types of dryer technologies in scientific literature [2,11,12,21], the variety of technology really used in the field is limited (Tables 4–6, Fig. 2).

The inventoried dryers were grouped into 10 types, and characterized by their data in Tables 7 and 8. According to the criteria classification of Table 1, all were small-scale dryers applied to solid products in a thin layer. They ran in batch or semi continuous mode, and were controlled manually.

The inventoried dryers could be classed according to six types of energy income modes and described in Tables 4–6.

3.1.1. *Sun drying*

Sun drying was the most used, representing 70% of the total dryers surveyed. This method uses a surface such as the ground, asphalt roads, cemented areas or tables (Table 4, 7). The use of a protective sheet (fabrics, trays, sieves or mats) facilitated product handling and avoided direct contact with the ground. A typical case involved drying on fertilizer bags. In some cases, products were covered with fabric to reduce insect and bird contamination (e.g. sun drying of coconuts covered with a fine net in Burkina Faso).

3.1.2. *Direct solar dryers*

Three types of direct solar dryers were found: tent, direct cupboard and greenhouse (Tables 5, 7 and 8). All their structures were made of wood. Covers were made of polyethylene film for tent and greenhouse dryers, and glass for direct cupboard sides. Table 7 shows that their capacities were limited from 5 to 20 kg of product which is lower than those of sun drying.

3.1.3. *Indirect solar dryers*

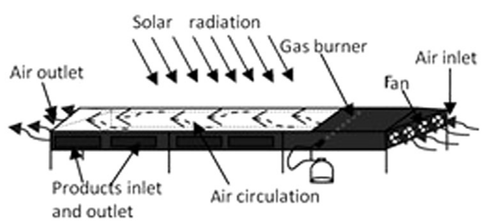
Despite the numerous research publications on indirect solar dryers [2,13,22], only two types of this model were found: the shell dryer and the indirect cupboard dryer (Tables 5, 7 and 8). All the Shell dryer manufacturers received the same training which resulted in the same design, two black painted metal cones joined by a hinge [30,63] (see Shell photo in Table 5). The indirect cupboard dryer was closer to the M5 003, a much-studied chimney dryer see [64]. It had a wooden structure, insulated with kapok, covered with sheet metal painted in black. In that solar dryer, the hot air circulation is reached through a glass cover solar collector and a chimney.

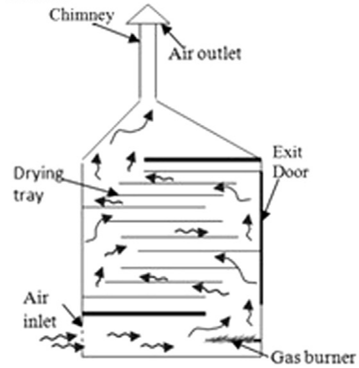
3.1.4. *Mixed solar dryers*

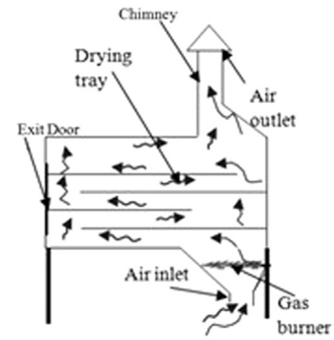
The mixed solar dryer was a dryer chamber (Tables 5, 7–8). Solar energy reached the products in two ways: through a transparent roof and via air coming through a solar collector.

Table 6
Listed hybrid and artificial dryers.

Mixed and hybrid solar dryer	Gas dryers	
Geho	Atesta	Maxicoq







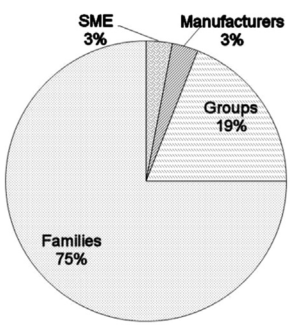


Fig. 2. Distribution of the population investigated.

The structure was built in cement. There were two glass cover solar collectors with black gravel absorbers on both the south and north sides. The black gravel absorbers enabled drying to be continued through the night or in cloudy weather [31,65]. Three chimneys were placed on the top to improve air circulation. It was used for rice and cassava drying.

3.1.5. Hybrid solar dryer

The Geho model is a mixed hybrid dryer adapted from the Hohenheim greenhouse tunnel dryer (Tables 6–8), with an additional gas burner and forced air convection using a fan [28,66]. It is used for foodstuffs based on cereals and tubers.

3.1.6. Gas dryers

Two types of gas dryer were used: the Atesta dryer in the three countries [18,35] and the Maxicoq dryer only in Benin and Burkina Faso (Tables 6–8). The Atesta was built with wood on a cement base and the Maxicoq dryer was made of iron sheets with wood insulation. These dryers are models respectively designed by the CEAS and Songhaï NGOs. The resulting quality of dried fruit (Table 8) rendered them suitable for export.

3.2. Dried products

3.2.1. Dried product types

Table 9 gives some drying characteristics of the dried products [6,67-71]. The FAO classifies agricultural products as: cereals, tubers, vegetables and fruits [73] and that classification is applied in Table 9. The microalga *Spirulina* was included in the vegetable category because of its high initial moisture content X_i. Data on initial X_i and final X_f moisture content was collected from existing literature [74]. In Table 9 the thickness indicates the average height of the product layer. The dimensions provided were measured in the field (on site at the producers and at the local market). X_i varies between 300 and 500 kg of water per 100 kg of dry biomass and varies from 30kg for cereals (millet, rice) to 1900kg water par 100 kg dry product for tomatoes. The sugar content in products varies from 0 to 27% (maximum for banana) and evokes various behaviours (crust formation, oxidation and the Maillard reaction) in products exposed to the same solar radiation and air temperature.

3.2.2. Mass water per unit area

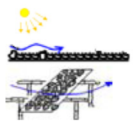
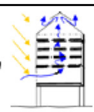
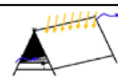
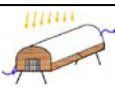
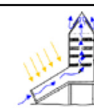
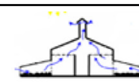
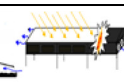
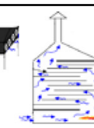
During the survey, it was found that it was mainly products with a low initial water content (cereals, legumes) and leaf-vegetables that were processed using direct solar drying [75,76]. This may have been related to the low mass of water per unit area of tray [77]. It could only be achieved with the other products by cutting them into very small pieces (not traditional sizes). Low mass of water per unit area of tray, together with low-concentration solar energy enable a moisture content after the first day of drying that is low enough to limit damage. Whatever the type of dryer, the operators were highly sensitive to product losses.

Fruits (pineapple, mangoes) and *Spirulina* have to be dried quickly at the beginning due their high initial moisture content and high carbohydrate content [72]. It is necessary to decrease water activity to less than 0.9 after a few hours or one day of drying, depending on the product. This might coincide with the transition between the first and second drying phases. The transition time between the first and second phase is not always well known and is determined by the experience of the users.

3.3. Types of dryer users

Out of the 140 visited structures in the three countries, users could be classed in three categories: (1) families, (2) groups (e.g. cooperatives) and (3) small and medium-sized enterprises (SME) (Table 10). Families mostly carried out drying for home-consumption and storage. Being in a recognized group (like a group (2) or SME (3)) helped in obtaining financial and technical support from governmental or non-governmental organizations

Table 7
Characteristic data on the listed dryers.

	Traditional drying devices	Direct cupboard	Tent	Green house	Shell	Indirect cupboard	Chamber	Geho	Atesta	Maxicoq
										
Energy used	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Gas	Gas
Ventilation	Natural	Natural	Natural	Natural	Natural	Natural	Natural	Forced	Natural	Natural
Tray position	Side by side	Super-posed	Side by side	Side by side	Super-posed	Super-posed	Side by side	Side by side	Super-posed	Super-posed
Air flow	Above product	Through product	Through product	Above product	Through product	Through product	Through product	Above product	Above product	Above product
Mode of operation	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch
In–dryer tray motion	Static	Static	Static	Static	Semi-continuous	Rotation	Static	Rotation	Rotation	Rotation
Dryer capacity (kg/cycle)	1 - 4000	5 - 10	5	20 - 30	5	30 - 40	2000	50 - 60	100	26
Number of trays	1	4	1	1	3	10	20	16	20	5
Single tray area (m²)		0.12;0.16; 0.24;0.40	3.35	3	0.15; 0.70; 0.70	0.5	1.6	0.71	0.84	0.84
Total tray area S_t (m²)	1- 625	0.92	3.35	3	1.55	5	32	11.4	16.8	4.2
Life span (year)	1- 20	5	3	5	10	5	20	10	10	10
Material	Mat, steel, cover, sheet, table, road	Wood, glass	Wood, polythene film	Wood, polythene film	Metal sheet, rod plastic lattice	Wood, metal sheet, glass	Masonry, glass, wood	Metal sheet, rod, plexiglas	Masonry, wood, metal sheet	Metal sheet, rod, wood
Dryer cost (€/m² of tray)	0- 7.63	83	9.11	66.2	73.9	45.8	239	108	182	179

(NGO). For all the inventoried SMEs, drying was their main activity. For Togo, the distribution of the surveyed population is presented in Fig. 3.

3.3.1. Families

Families dried in the family surroundings for conservation and also for sale. They comprised crop producers in rural areas [11,15], urban and rural families, as well as shopkeepers. All products except fruits were dried (cereals, cassava, sesame, coconut, vegetables such as okra, pepper). The labour employed was limited to members of the family. The operations consisted of placing the products in thin layers, with permanent surveillance against animals, in the event of rainfall and with regular turning of the products to standardize drying.

3.3.2. Groups

There were three types of cooperative groups: truck farmers, women and agricultural producers:

- Truck farmers often dried unsold products or surplus production. They all used Shell dryers and indirect cupboards. The dried products were sold at local markets.
- For women's groups, drying was a profitable activity and was applied to mangoes, papayas, bananas and vegetables such as tomatoes, onions, okra and chilli. They used shell dryers, direct cupboards and greenhouse dryers.
- Agricultural producers were farmers who ran several farms together. They mostly dried cereals and tubers to store them for later sale. They used traditional sun drying systems, such as concrete areas.

Table 8
Operating data for listed dryers (C: cereal; T: tuber; V: vegetable).

Dryer types	Sun drying	Direct solar dryers			Indirect solar dryers		Mixed solar dryers	Hybrid solar dryers	Solar dryers	
Dryer	Traditional drying devices	Direct cupboard	Tent	Greenhouse	Shell	Indirect cupboard	Chamber	Geho	Atesta	Maxicoq
Energy	Exposure to direct solar radiation (variable areas)	Total surface 1 m²	Total surface 2 m²	Total surface 3 m²	Total surface 1 m²	Total surface 2 m²	Total surface 81 m²	Total surface 2.6 m² + 0.5kg/h gas	0.5kg/h gas	0.5kg/h gas
Dried products	C: maize sorghum millet T: cassava V: okra pepper	V: onion carrot cabbage tomato pepper okra	V: onion pepper okra	V: onion cabbage tomato pepper okra ginger carrot F: coconut	V: onion carrot cabbage tomato pepper okra F: papaya mango banana	V: onion cabbage tomato pepper okra ginger carrot	C: rice T: cassava	C: maize millet T: cassava yam	F: mango, pine-apple, papaya, banana	T: cassava yam F: mango
Initial form of product	Grain Slice Piece	Leaf Slice Piece	Slice Piece	Leaf Slice, dice Piece	Leaf Piece Slice	Leaf Piece Slice	Grain Piece	Grain Piece	Slice	Slice Piece
End use	Home consumption, local market	Local market	Local market	Local market	Local market	Local market	Local market, export for cereals	Local market	Export, local market	Export, local market
Drying time (day)	Several days	1–3	2–3	1–3	2–3	2–3	3 (cereal)	1–2	1	0.5
Max. Temp. drying air (°C)	Ambient 28–35	50	45	50	50	55	70	80	80–90	80–90
Operating cost (€/year)	0–1.53	0.76–3.05	1.53	7.63	5.34	9.16	15.27	973	1,867	486
Climatic zone	All zones	Sudan-Sahelian	Sudan-Sahelian	Sudan-Sahelian	Sahelian and Sudan-Sahelian	Sudan-Sahelian	Humid tropical	Humid tropical	All zones	Humid tropical

These groups were often helped by NGOs to improve their activities with regard to hygiene, pre-treatments, control of the dryers, the packaging of dry products and financial management.

3.3.3. The small and medium-sized enterprises (SME)

Different NGOs promoted drying for export or for the local market. This was presented as an economic project needing investment and ensuring effective procedures. Atesta dryers were used for mangoes, pineapples, bananas, papayas and *Spirulina* for the local market and exports. Maxicoq and Geho dryers were used to dry cereals and tubers for the local markets.

Initially, the labour was trained by the NGOs using their demonstration equipment. The equipment, often a single model, was manufactured and installed by craftsmen or by NGOs. The units were initially equipped with one or more dryers. To increase output, they increased the number of dryers. The dryer monitors had to preheat the dryers, decide the workload between the different dryers, permutation or rotation of the trays, modulation of the drying conditions and removal of the trays at the end of drying. According to the managers we met, controlling the dryers (by flow gas and air temperature control) was a key position, requiring intelligence, meticulousness and care. For all the other stations, like cleaning, weighing, pre-treating, arranging on the trays and packaging, only strict hygiene was necessary.

3.3.4. Dryer choice by users

The choice of dryers made by the various users seemed to be governed by factors other than the criteria presented in Tables 1 and 2. According to Fig. 3, only the traditional systems with direct exposure to the sun, the Shell dryer and the Atesta dryer were found in all the surveyed zones. The other types of dryers were only present in very limited areas.

Some non-directive discussions with the users provided the following explanations. The Shell and Atesta dryers were the subject of long and wide-ranging dissemination campaigns, reaching the surveyed areas. These actions were initiated in Europe by the NGO GERES, France, for the shell dryer and CEAS, Switzerland, for the gas dryer [78]. They were first promoted in Burkina Faso, by the NGOs ABAC and ATESTA, respectively. They then extended their dissemination to the sub-area, particularly in Benin and Togo. In the latter country, the NGO Rafia made a donation to women's groups of shell dryers bought in Burkina Faso at a price of € 115 each and cupboard dryers at € 76. In Benin, the government financed the provision of Atesta dryers for 35 groups and SMEs.

For the other types of dryers found only in some limited areas (Fig. 3), their dissemination was due to the local promoter's action. In Togo, the greenhouse dryer was used by groups located near the manufacturer, who promoted it to potential users and NGOs. In Benin, it was the Songhaï Centre that was at the origin of the Geho and Maxicoq dryers, in connection with projects. Edoun et al. [79] reported that in the South of Cameroon, 42% of users were more likely to use dryers they had seen operating, and 34% were influenced by the source of energy of the dryer. These percentages show that promotion and training on the models of dryers had a strong influence on the dissemination of those models.

3.4. Environmental specifications

The majority of stakeholders chose where they conducted their drying operations. The advantages quoted by the rural operators were the proximity of supplies and low labour costs. The urban

Table 9
Products dried.

Dried products	Initial moisture content X_i (dry basis, %)	Final moisture content X_f (dry basis, %)	Sugar content (g/100 g) [67, 74–78]	Max. drying temperature (°C) [11,19,20]	Form	Diameter, (cm)	Thickness, (cm)
Cereals							
Maize	32–54%	14–18%	3.64	60	Grain		3–7.5
Rice	32%	12%	0.13	50	Grain		< 2.5
Sorghum, Millet	27%	16%			Grain		1.5–6.5
Tubers							
Yam	233–400%	11–16%	5.8–7.2	65	Slice		4–7.5
Cassava	163–233%	11–20%	3.9		Slice		4–7
Fruits							
Pineapple	400–567%	14–11%	6.4–14	65	Slice		3–7
Banana	257–400%	14–18%	14.8–27	70	Slice	3–3.5	0.5–4
Mango	400%	14–19%	13–16	70	Slice	0.5–1.5	
Papaya	400%	14–19%	7.6–7.8	70	Slice		
Vegetables							
Cabbage	400%	5%	2.8–3	60–65	Slice		
Carrot	233%	5%	6.7	75	Slice	2.5	2
Tomato	1,900%	8%	2.8–3.5	50–60	Slice		
Pepper	245–567%	5–15%	2.2–4.7	70	Slice, piece	1.5–4	2–5
Onion, garlic	400–565%	4%	7.10–8.2	55	Slice	3–7.5	
Green beans	233%	5%	2. 6–4.6	75	Slice, piece	4.5–7	0.4–0.7
Okra	400–669%	12–18%	5.5	66	Slice, piece	2.5–4	3–4.5
Ginger	400%	11%	9.8		Slice, piece		
Leaf-vegetables	400%	11%		60	Leaf		< 4
Spirulina (microalgae)	400%	9%	15–20	40–60	Pasta in cylinder	0.2	0.2

Table 10
User typology.

Users	Used dryer type	Product type	Kg of humid product per cycle, $m_{i,cy}$	Purpose of drying (outlet)	Investment capacity (€/dryer)	Organization / Qualification level
Family	Traditional drying	Cereals Tubers Vegetables	500–2,000 100–500 1–10	Home consumption Local sale	23	No knowledge or experience required Periodic checking of the drying
Craft, Group	Traditional drying	Cereals (farmers), tubers (farmers)	> 1,000	Local sale	76	No knowledge or experience required but training of the labour
	Tent, shell, cupboard	Fruits, vegetables (truck farmers and women)	50–100			Periodic drying checks
Small scale industrialized companies	Chamber	Cereals	> 1,000	Exports	≤3,053	Basic training course required to read a thermometer and note the indications.
	Geho, Maxicoq Atesta, Maxicoq	Tubers Fruits	25–100 25–100	Local sale		Regular drying checks

operators chose to be close to the final market, being able to have varied raw materials and having access to more educated labour with greater experience. As regards the equipment, unlike rural zones, the urban area for dryers was mostly exploited vertically. That reduced the potential use of solar energy, the only free surfaces being roofs. Thus, in urban areas, dryers were compact, with superimposed trays; solar dryers were used for small capacities and gas dryers for large capacities.

All the dryers used were built exclusively with materials available in the country (Table 7). For sun drying, materials were almost free and usually nearby. For direct and indirect solar dryers, the materials were available in most towns. Using local materials made the dryers cheaper and reassured users about the maintenance of the dryer [58]. For more efficient dryers, technical parts such as glass (solar dryer) and fans were only available in large urban centres and their cost was relatively high. As indicated by [80,81], those differences helped to explain the large proportion of low technology dryers found in our survey (Table 7).

3.5. Energy used

3.5.1. Type of energy

Two sources of energy were widely used: solar and gas energy. Three dryer categories appeared: the dryer using only solar energy (7 out of 10 dryer types), those using only gas energy (2 out of 10 dryer types), and one using both solar and gas energy (biomass use for energy was not found; it is a practice that exists in the South of Cameroon, a densely forested zone [79]).

3.5.2. Availability, cost and constancy

The availability and cost of energy sources were constraints for the choice of a dryer. Also the constancy of the heat supply induced a risk for product quality and dryer efficiency:

– Solar energy is free but its variability and irregularity do not enable the standard quality required on export markets to be achieved. The mean solar radiation calculated from the three

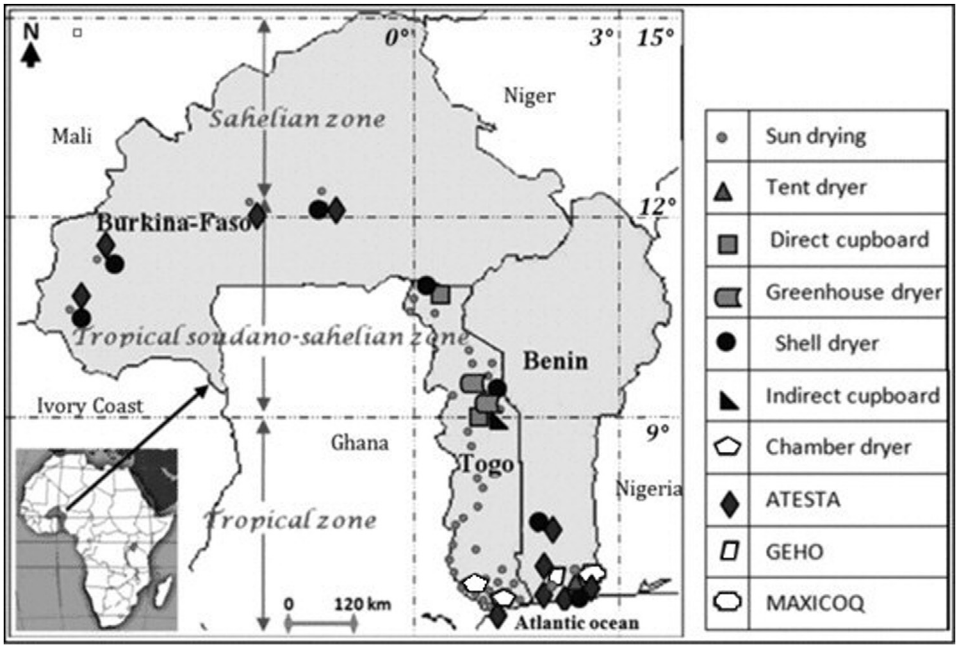


Fig. 3. Geographical distribution of the inventoried dryers.

recording stations in Togo were: 15,883 kJ/m^2 d for Lomé at the 6th latitude north, 17,078 kJ/m^2 d for Atakpame at 7°53′ latitude north and 19,040 kJ/m^2 d for Mango at 10°27′ latitude north. Sun or solar dryers were not used to dry fruit for export (Table 8).

– Gas gave a high drying power for a low investment. For users such as SMEs which bought the raw material, the adoption of gas dryers was recommended so as to avoid low-quality products or losses which drastically decreased their profit. In the three countries of the survey, gas was subsidized to fight against desertification.
– Hybrid dryers used both energies and theoretically combined their advantages: gas had to be used only to compensate for a lack of sun power. A *Spirulina* drying unit in Burkina Faso preferred to begin drying in a non-insulated indirect solar dryer and then transfer the trays to an Atesta dryer to finish. To produce cassava pasta in Benin, another SME heated its Geho dryer with gas all day except during high solar radiation periods.

Depending on energy availability, the survey showed that solar dryers were more numerous in the northern areas, where the hot and dry climate is more suitable [81]. In the coastal zones, where the tropical climate is humid, SMEs primarily used gas dryers (Atesta, Maxicoq and Geho). However, cemented areas measuring 25×25 m^2 were seen in the Zio valley in Togo, introduced by Asians for rice drying. A chamber dryer was also found. It had a large collector area of (49 m^2) compared to the area of its trays (32 m^2) and the dried products, mainly rice, were a little damaged during long periods of drying [31].

3.5.3. Energy for ventilation

Forced convection makes it possible to increase the drying rate at the beginning of drying for products with a high water content [82–84], to improve uniformity between products and make energy savings by re-circulating some of the drying air. Although almost all proposed dryers for developed countries are equipped with ventilation, out of those listed in our survey, only the Geho dryer used it (Table 7). For this dryer, four fans were powered by a car battery charged in town. On the greenhouse dryer, it was optional and powered by a 2.5 W panel. The scarcity of an electrical supply network in the rural areas of West Africa [13,85] and the great irregularity of supplies force users to be autonomous. That requires major investments, and the cost of electricity is very high. Whenever ventilation is stopped (due to frequent power outages of the electricity network), there is a risk of fire hazards because gas heating continues [25].

The survey did not identify any wind-ventilated dryers, which are used in some developing countries such as India [13,86,87].

3.6. Drying specification

3.6.1. Dryer operation mode

During sun drying, the product has to be turned manually according to the quality of its appearance and its exposure to the sun and the weather. These interventions ensure uniform drying even with the lowest technology level. All the inventoried dryers were static (Table 7). For most uses, the operators had only two tasks per day: loading and unloading. For drying times exceeding one day, only the shell dryer was used almost as a semi-continuous process: dry air comes first into contact with already partially dried products and then with fresh products just placed in the dryer [30]. For the Atesta, Maxicoq and Geho dryers, trays were regularly permuted or rotated to obtain uniformity in the drying process and prevent dry products from burning.

To achieve continuous operation, another energy supply had to be added. The corresponding technology level and investment was too great compared to the size of the units visited. Desmorieux et al. [88] proposed a semi-continuous gas dryer for 500 kg of fresh mangoes (21 kg/h) in accordance with one user's needs, considering all the operations before and after drying. The non-automatic device needed a high investment but represented a possibility for progressive evolution.

3.6.2. Drying air temperature

It is well known that the higher the temperature is, the higher the drying rate will be [82]. According to the operating temperature, dryers could be classed in two categories, although all the dryers listed were operating under 100 °C (Table 1).

- With the solar dryers, the classic air drying temperature was 45 °C to 55 °C; the highest would appear to be 70 °C (Table 8). High temperatures were obtained with a combination of high solar radiation, good thermal insulation (cupboard dryer), and a large collector area (1.5 m^2 of collector area per m^2 of drying tray in chamber dryers).
- With the gas or hybrid dryers, the drying temperature could be higher than 80 °C (Table 8) to obtain a high drying rate until the product began to change texture without damage [20]. This temperature was higher than those given in the literature [89–92]. This is possible during the first period of drying because the product surface is still humid, and its temperature does not rise above the air temperature. According to this phenomenon, at the beginning of drying, pineapples and mangoes are dried at 80 °C and *Spirulina* at 60 °C. For example, in the southern locations of the survey (in a humid tropical climate), the characterization of the ambient air could be 35 °C, 95%. By heating that air to 80 °C, the relative humidity of the air drops to 11% and the wet bulb temperature reaches 40 °C, lower than the maximum dry air temperatures given in Table 9. The maximum operating temperature indicated by the literature (Table 9) was not strictly followed. High temperatures increase the nutritive element degradation rate but shorten the drying time. *Spirulina* dried at 60 °C loses 30% proteins, compared to 20% at 40 °C [93].

3.6.3. Initial product mass flow

The flow of product dried in a dryer is useful information for potential users and those who advise them. With solar dryers the elements determining the flow of dried product are the collector area, its efficiency and the area of the trays. For gas dryers, it is the gas consumed and dryer efficiency. The drying flows as defined in Section 2.3 for the various dryers are shown in Table 11. The product flow increases from solar dryers to hybrid dryers and gas; the chamber dryer is an exception (Table 11). This was confirmed by Janjai et al. [94] with a PV-ventilated solar greenhouse of 40.4 m^2 which dried 100 kg of bananas in 4 days compared to 6 days with sun drying. With the ratio of flows in relation to tray areas m_{i,d_t} or to collector areas m_{i,d_s}, it turned out that:

- For sun drying, because the areas exposed to the sun and the tray area are the same, the average initial product mass flow express per m^2 of projected area as per m^2 of tray (m_{i,d_t} or m_{i,d_s}) are the same: from 1.5 kg/d m^2 to 4.2 kg/d m^2 (Table 11). For the tent dryer, the direct cupboard, the shell dryer, and the Geho, the ratio between the tray surface and the projected collector area perpendicular to solar radiation is close to one. The mass flows m_{i,d_t} per m^2 of tray were similar to the mass flows m_{i,d_s} per m^2 of projected area perpendicular to solar radiation (Table 11). They vary between 0.5 and 3.4 kg/d m^2. But for the indirect cupboard, the mass flow m_{i,d_t} per m^2 of tray (1.3 kg/d m^2 to 2 kg/d m^2) was lower than that per m^2 of projected area m_{i,d_s} from 4.2 kg/d m^2 to 6.3 kg/d m^2 (Table 11). The opposite remark can be made for the chamber dryer, where the mass flow m_{i,d_t} per m^2 of tray (31.3 kg/d m^2 to 15.6 kg/d m^2) was higher than that per m^2 of projected area m_{i,d_s} from 6.3 kg/d m^2 to 12.6 kg/d m^2 (Table 11). This shows that the indirect cupboard dryer was undersized and the chamber dryer was oversized.
- For the gas dryers, Atesta and Maxicoq had almost the same gas flow (12.5 kg/d). The Atesta mass flow was twice that of the Maxicoq.

Together, these givens highlight the fact that there is no simple, defining rule related to product drying, given the capacity of a dryer in relation to its principles of functionality and dimensions (size).

3.7. Dryer cost

The dryer cost depended on the technology involved, on the user's investment capacities, on the initial product mass flow and on the outlets for the dried products. Depending on the reference, the costs can be expressed by the investment cost by tray area, by year and by product mass flow, Tables 7, 8 and 11.

All the dryer prices ranged between two extremes; the sun dryer cost, from zero to € 7.63/m² of tray and the chamber dryer price, which was the most expensive (€ 182/m² of tray) (Table 7). Three types of dryers could be distinguished when considering their investment cost in relation to their capacity (according to the tray area):

- Sun drying, the common system that every family could potentially use. With almost no cost and no payback period, its operating cost was under € 1.53/year (Table 7).
- Most solar dryer costs were between € 9.11 and € 83/m² of tray, except for the chamber dryer which was € 239/m^2 of tray (Table 7). The operating cost of solar dryers ranged from € 0.76 to € 15.3/year (Table 8).
- The last category concerned gas and hybrid dryers. Their costs ranged from € 108 to € 182/m^2 of tray (Table 7). The dryers were manually controlled and additional energy made drying more expensive. The operating cost ranged from € 486 to € 1867/year (Table 8).

When related to the product mass flow, the comparison of the dryer investment costs $P_{dryer,p}$ showed a different classification in Table 11:

Table 11
Drying flow and investment cost of inventoried dryers.

		Sun drying	Direct cupboard	Tent	Green-house	Shell	Indirect cupboard	Chamber	Geho	Atesta	Maxicoq
Drying flow $m_{i,d}$											
(kg/d)	Max	16.7	5	2.5	10	10	2.5	1000	60	100	52
	Min	–	1.7	1.7	6.7	6.7	1.7	667	30	120	
Drying flow/tray area m_{i,d_t}											
(kg/d m²)	Max	4.2	5.4	0.7	3.3	1.6	2	31.3	5.3	–	–
	Min	1.5	1.8	0.5	2.2	1.1	1.3	15.6	2.6	–	–
Drying flow/collector area m_{i,d_s}											
(kg/d m²)	Max	4.2	5.5	1	3.4	2.8	6.3	12.6	4.2	–	–
	Min	1.5	1.8	0.7	2.2	1.9	4.2	6.3	2.1	–	–
Dryer price/mass flow $P_{dryer,p}$											
(€ d/kg)	Mean	0.5	30.5	15.3	24.8	57.3	28.6	11.5	30.5	28	14.4

- Sun drying still had the lowest cost of investment by mass flow of product $P_{dryer,p}$ at less than €1 d/kg. than €1/(kg/d).
- But due to a high mass flow, now the chamber and Maxicoq investment costs per mass flow of product $P_{dryer,p}$ came close to the cost of the tent dryer, between € 10 and € 15.5 d/kg (Table 11) and presented some viable options for dryer types. The direct and indirect cupboard, the greenhouse, the Geho and the Atesta dryers all had a similar investment cost per mass flow of product $P_{dryer,p}$ at between € 20 and € 30.5 d/kg (Table 11). In this comparison, it was the shell dryer that had a much higher cost when we looked at the dryer price per product flow $P_{dryer,p}$. It showed that the investment made in the shell dryer was too high compared to its efficiency (mass flow of product).

3.8. Dryer classification with proposed criteria

This study showed that all tropical food dryers are applied to solid food and, according to the classification of Table 1, they belong to small-scale dryers up to 1000 kg/cycle.

Many criteria characterize drying situations as shown in Tables 1 and 2. Those criteria have to be taken into account for the choice of a dryer or for design. The most significant criteria are the type of dried product and the drying purpose, followed by financial investment capacity. Subsequently, it is necessary to consider the source of locally available energy, the required dry product flow and all other criteria concerning the manufacture and operation of the dryers.

In his study on *Spirulina* drying in Chad, Yacoub [95] showed that an adapted dryer totally depends on the product used and the market. It is so significant that the product can be considered as new for each different purpose and design processes must be adapted.

So, in addition to those proposed in the literature (Table 2), some new criteria needed to be considered. The criteria that are usually taken into account concern the product, user, the social and economic environment, energy, surroundings, dust and humidity, along with criteria for energy, drying rate, batch or continuous mode, dryer air temperature, energy efficiency, availability and physical characteristics of local material, ease of product access, and ease of loading and unloading. In addition, the purpose of the dried product, initial moisture, product composition, the possible investment capacity of users, the maximum available dryer cost, operating cost per kg, energy supply availability and regularity, the corresponding training level of the labour for the dryer, the available space on the ground, all have to be considered.

For a design methodology including a functional characterization of a dryer, as has been done, or for selecting an appropriate dryer, the system has to be extended to the user, the environment and the product outlet. A classification of criteria and inventoried dryers is proposed in Table 12.

3.9. Profitability of dryers analyzed in situ

It has to be said that many dryers were not used for more than two to three years or, at least, were not renewed [72]. The analysis of dryer dissemination in Section 3.3.4 shows that the use of non-traditional dryers by users was determined by promotion and dissemination operations. It therefore appeared essential to check that one condition required for their continued use and, at best, for their renewal, was economic profitability. To that end, six typical dryers were effectively characterized: the protective sheet dryer (traditional solar device), the direct cupboard dryer (direct solar), the shell dryer (indirect solar), the chamber dryer (mixed solar), Geho (mixed gas and solar) and Atesta (gas). They are presented in Tables 5–8. Table 13 gives the data resulting from the survey and the literature used for calculations. The characteristics of the analysis of the six drying situations are presented in Table 14.

3.9.1. Traditional drying on a protective sheet

The case considered was maize drying on fertilizer bags as described in Section 3.1.1. In spite of high solar radiation of 17 MJ/m^2 d (Table 13), the evaporated water flow of the 4 m^2 of sheet was estimated at approximately 2.5 kg/d (Table 13). Its efficiency ε was estimated to be 8%. This and its P_{dryer} purchase price were the lowest of the six dryers (Table 14). The cost of drying $C_{dry,w}$ at about € 0.01/kg of evaporated water accounted for 7% of the capital gain (Table 14), with wet maize having a very low value. This dryer presented a risk of product deterioration by birds and also in the absence of sunshine. In spite of this disadvantage, use of the protective sheet dryer in particular, and traditional drying systems in general, were seen to be profitable and continued to be extensively used to dry harvested products for self-consumption, storage or local marketing.

3.9.2. Shell dryer

The shell dryers considered were those received as a donation from the Rafia NGO by the women's groups in northern Togo. They cost € 115. Their use was currently limited to drying vegetables (tomatoes, carrots, peppers, etc.) in the dry season (100 days per year) (Table 13). The solar collector area, of 1 m^2, was exposed to solar radiation of 20,286 kJ/m^2 d (Table 13) and led to the elimination of 1.6 kg/d of water with an efficiency ε of 19% (Table 13). The economic calculations, including depreciation and maintenance, led to a drying cost $C_{dry,w}$ of € 0.10/kg of evaporated water (Table 14), the highest value for the analyzed dryers. The activity achieved a negative capital gain value CG_d of € -0.14/d (Table 14). As maintenance costs were low, the activity was sustained but there was no plan to renew the dryer. In our survey of these dryers, several groups stopped their activity when the dryers started to break down.

3.9.3. Direct cupboard dryer

The donation of direct cupboard dryers to women's groups using the shell dryers donated by the Rafia NGO was intended to enable an increase in production and an improvement in the quality of the products by shortening the drying time. These objectives were not achieved; the only improvement was the inspection of the products without opening the dryer. At a cost of € 76, the direct cupboard had an evaporation flow M_w of 1.3 kg of water per day with 15% efficiency ε (Table 14). The drying cost $C_{dry,w}$ was € 0.07/kg of evaporated water (Table 14). This cost led to a negative capital gain. The use and prospects for renewal were therefore equivalent to those of the shell dryer.

3.9.4. Chamber dryer

The chamber dryer considered was a prototype resulting from research by the solar energy laboratory at the University of Lomé [31]. It was installed in a small SME whose main activity was producing and processing rice, including drying and selling on the local market and for export.

The high dryer purchase price P_{dryer} of € 7634 led to relatively low depreciation because of 284 days use per year (three harvests) and a life span of 20 years. Its efficiency estimated to be 23% appeared very high, and may have been due to energy storage inside the dryer. All the energy received by the dryer, and not used, was used later, for example during the night. This was not the case with the traditional solar dryer. Aboul-Enein et al. showed that the storage of energy in a solar collector (with granite) at least makes it possible to double the time during which the average temperature at the outlet of the collector is higher than the average

Table 12
Classification of criteria applied to inventoried dryers (C: cereal; T: tuber; V: vegetable; F: fruit).

Criteria	Sun drying	Direct cupboard	Tent	Green-house	Shell	Indirect cupboard	Chamber	Geho	Maxicoq	Atesta
1st level criteria: product specifications										
Type[1]	C, T, V	V	V	V	V	V, F	C,T,V	C, T, V	C, T, F	V, F
Initial moisture content (dry basis, %)	27–669	233–1,900	233–1,900	233–1,900	233–1,900	233–1,900	27–1,900	27–1,900	27–567	233–1,900
Composition										
Heat sensitive[2]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Light sensitive[2]	Depends on dryer model	✗	✗	✗	✓	✓	✗	✗	✓	✓
Quick deterioration[2]	✗	✗	✗	✗	✗	Depends on loading	Depends on loading	✓	✓	✓
Drying flow [4] Quantity[3] × frequency[3]	Low	Low	Low	Low	Low	Low	High	Medium	High	Medium
2nd level criteria: economic specifications										
Investment capacity[5s]	Low	Medium	Medium	Medium	Medium	Medium	High	High	High	High
Dried product outlet	Home consumption Local market	Local market	Local market	Local market	Local market	Local market	Local market Export	Local market Export	Local market Export	Local market Export
3rd level criteria: environmental specifications										
Energy availability	●○	●○	●○	●○	●○	●○	●○	○,some rural area	○, some rural area	○, some rural area
Material availability	●○	⦿	⦿	⦿	⦿	⦿	⦿	⦿	⦿	⦿
Space availability	●○, limited in urban area	●○	●○	●○	●○	●○	●	●	●○	●○
Technician availability	●○	●○	●○	●○	●○	●○	●○	⦿	⦿	⦿
Climatic zone ambient air characteristics	✦ ▲, less in wet climate	✦ ▲, less in wet climate	✦ ▲; less in wet climate	✦ ▲, less in wet climate	✦ ▲, less in wet climate	✦ ▲, less in wet climate	★✦ ▲	★✦ ▲	★✦ ▲	★✦ ▲
Solar energy constancy (dry season)	Good	Good	Good	Good	Good	Good	Good	Good	–	–
Technical requirements	None	Limited	Limited	Limited	Limited	Limited	Limited	Training in-field	Training in-field	Training in-field

✓ Yes.
✗ No.
○ Urban area.
● Rural area.
⦿ Rural and urban area.
●○ Rural or urban area.
★ Well adapted to tropical humid climate.
✦ Well adapted to Sudan-Sahelian tropical climate.
▲ Well adapted to Sahelian climate.

[1] Type of product that can be dried with the inventoried dryers.
[2] Can be dried with the dryer in question.
[3] Supply quantity/supply frequency.
[4] Low: <30 kg/d ; medium: 30 kg/d to 100 kg/d; high: $>>100$ kg/d.
[5] Low: $<$€ 1.5/m²; medium: € 9/m² to € 83/m²; high: € 107/m² to € 182/m² (m² of tray).

temperature of a collector without storage [96]. The evaporating capacity M_w of the chamber dryer, at about 152 kg/d, was high (Table 14). The drying cost $C_{dry,w}$ was thus estimated to be € 0.01/kg of evaporated water, the lowest of the dryers analyzed. As rice is rarely marketed in its wet state, the high capital gain achieved CG_d, at € 640/d was only indicative (Table 14). By relating the cost of drying to the turn-over, we obtained approximately 1%, still very low.

The high cost of construction P_{dryer} was not conducive to its reproduction. The company preferred building cemented drying areas and equipping them with protective sheets, in order to protect them in the event of rain. It was looking for a solution with lower investment and a capacity of about 5000 kg/drying cycle.

3.9.5. Geho dryer

Only one Geho is used in the surveyed region, that dryer belonged to a Beninese SME processing tubers (cassava, yam) and cereals (corn, sorghum) into pasta sold in supermarkets. This dryer model was chosen and constructed by the Songhai Centre in Porto-Novo. For the calculation, the product chosen as a reference was the cassava-based pasta. For that product, dried mainly during the dry season, the Geho eliminated 49.5 kg of water per day (Table 14). Incoming solar radiation was complemented by adding roughly the same amount of energy as burning 4.6 kg of gas per day. Its overall energy efficiency ε was 25% (Table 14). It could be optimized if gas use was solely in addition to complete solar energy in two cases: if the products were very wet or if the weather was very bad. The purchase price for the Geho was € 1221. With approximately 180 active days per year, the drying cost $C_{dry,w}$, at € 9/kg of evaporated water (Table 14) was equally divided between the cost of gas and the cost of depreciation. Although it was high, it only amounted to 9% of the capital gain.

The activity was profitable and there was no risk in this production. The SME would like to invest in the future to obtain more uniform and rapid drying.

3.9.6. Atesta dryer

The CEAS (The Albert Schweitzer Ecological Centre) in Ouagadougou, Burkina Faso, proposed this equipment to interested customers, together with training and openings towards exports

Table 13
Operating characteristics of six analyzed dryers.

Dryer	Atesta	Geho	Chamber	Shell	Direct cupboard	Cover dryer
Product	Pineapple	Cassava pasta	Rice	Tomato	Tomato	Maize
Humid product cost P_{RM} (€/kg)	0.15	0.31	0.14	0.15	0.15	0.15
Dried product cost P_{DP} (€/kg)	4.03	3.31	0.92	1.83	1.83	0.27
Variability of a drying cycle duration (h)	24–26	15–18	22–24	18–27	9–18	36–45
Mean duration of drying cycle Δt_{cy}, (h)	24	18	24	27	14	45
Mass loaded, (kg/m² tray)	6	13.2	31	3.2	2.2	12.5
Product mass precision (kg/m² tray)	± 0.5	± 1	± 1	–	–	–
Total tray area per dryer S_t, (m²)	16.8	11.4	32	1.55	0.92	4
Mean number of drying days per year $N_{d/y}$	365	180	284	100	100	90
Variation in number of days' use per year	200–365 days depends on raw material supply	Depends on orders; can exceed 180 days	200–284	90–100	90–100	30–90
Energy (gas/direct/ indirect)	Gas	Mixed solar + gas	Mixed solar	Indirect solar	Direct solar	Direct solar
Solar radiation I (kJ/m² d)	–	15,900	15,900	19,000	19,000	19,000
Projected collector areas perpendicular to solar radiation (m²)	$S_{dir}=0$ $S_{ind}=0$	$S_{dir}=11$ $S_{ind}=3$	$S_{dir}=31$ $S_{ind}=48$	$S_{dir}=0$ $S_{ind}=1$	$S_{dir}=1$ $S_{ind}=0$	$S_{dir}=4$ $S_{ind}=0$
Main components entailing maintenance costs	Tray, rubber seal for airtightness of door	Tray, airtightness between cover	Tray	Tray, coating	Tray	Support
Annual maintenance cost C_{maint} (€/year)	15.3	15.3	7.7	4.6	0.8	0.3
Other products dried with the same dryer	Mango, pineapple, banana	Pasta made out of maize, sorghum, yam	Maize, cassava	Pepper, onion, okra, vegetable leaves	Pepper, onion, okra, vegetable leaves	Sorghum, rice, cassava

Table 14
Thermo-economic analysis of six dryers.

Dryer	Atesta	Geho	Chamber	Shell	Direct cupboard	Cover dryer
Products to be dried	Pineapple	Cassava pasta	Rice	Tomato	Tomato	Maize
Dryer data						
Dryer cost C_{inv} (€)	3050	1220	7630	115	76	6
Life cycle Δt_{life} (year)	10	5	20	10	10	2
Annual maintenance cost C_{maint} (€/year)	15.3	15.3	7.6	4.5	0.8	0.3
Number of days of dryer use per year $N_{d/y}$ (d/year)	360	180	284	100	100	90
Operating						
Humid product initial mass per cycle m_i (kg/cycle)	120	150	2000	5	2	50
Initial moisture content X_i (dry basis)	400%	223%	32%	1718%	1718%	54%
Final moisture content X_f (dry basis)	14%	10%	12%	12%	12%	15%
Raw material cost per day m_{RM} (€/d)	0.15	0.31	0.14	0.15	0.15	0.15
Dried product price per kg P_{DP} (€/kg)	4.03	3.31	0.92	1.83	1.83	0.27
Drying time Δt_{cy} (d/cycle)	1	2	1	3	1.5	5
Theoretical calculation						
Energy received per day by the dryer E (kJ/d)	575,000	439,900	1452,300	18,200	18,600	67,700
Water mass evaporable by the dryer E/L_V (kg/d)	256	196	646	8.1	8.3	30.1
Practical calculation						
Final mass of dried product per day m_f (kg/d)	27	26	848	0.1	0.1	7.5
Daily evaporated water mass from the product M_w (kg/d)	92.6	49.5	152	1.6	1.3	2.5
ε = Evaporated water mass/evaporable water mass	36%	25%	23%	19%	15%	8%
Daily turn-over TO_d (€/d)	110	85	777	0.19	0.15	2.05
Drying cost per kg of evaporated water C_{dry} (€/kg)	0.07	0.09	0.01	0.10	0.07	0.01
Daily capital gain CG_d (€/d)	73.7	54	640	−0.14	−0.36	0.53
Part of drying cost in capital gain $C\%_{dry}$ (%)	8%	9%	0.2%	–	–	7%
Dryer cost/daily evaporated water mass (€ d/kg)	33	25	50	73	61	2.4
Profit per evaporated water mass (€/kg)	0.7	1.0	4.2	−0.2	−0.4	0,2

for products respecting a standard quality. All Atesta dryers have same sizes and capacities. The numerous successes in various countries facilitated the decision to invest, with the prospect of rapid returns and good profitability.

The values used for the Atesta dryers in our survey came from a unit which dried pineapples. The person in charge of the unit, trained with the CEAS, initially bought two dryers, and then added six other dryers built by craftsmen approved by the CEAS. Each dryer received 120 kg of fresh pineapple slices per 24 h. Its 36% efficiency ε was the best of the six dryers analyzed with an evaporative flow of 92.6 kg/d. Dryers were used throughout the year. The purchase price P_{dryer} was € 3053. Depreciation and maintenance were low compared to gas consumption which accounted for 86% of the drying cost $C_{dry,w}$, which was € 0.07/kg of evaporated water. This value, close to that of the Geho and chamber dryers, accounted for only 8% of the capital gain (Table 14).

International development of the Atesta dryer throughout French-speaking West Africa is a sign of success due to the various qualities of the equipment but also to the support provided through training and assistance with dried product marketing.

3.9.7. Thermo-economic synthesis

The ratio $P_{dryer,w}$ of the purchase cost for the various dryers to their evaporative flow made it possible to compare the investment

necessary for their performance (Table 14). The graph in Fig. 4 represents the daily benefit obtained for each drying situation, considered in relation to the average daily evaporative flow Pt_w, based on the purchase cost, also considered in relation to the daily evaporative flow $P_{dryer,w}$.

With identical evaporative capacity, the protective sheet (traditional) dryer was the least expensive dryer with a cost of € 2.4 d/kg of evaporated water; the profit was rather low at about € 0.2/kg of evaporated water. Using the protective sheet dryer (sun drying) as the reference, the Shell solar dryer and the direct cupboard were 25 to 30 times more expensive. They were the most expensive of the six dryers analyzed. With costs of € 73.2 d/kg and € 61 d/kg of evaporated water respectively, these dryers were not profitable for the activities for which they were being used. For the Geho hybrid and gas Atesta dryers, their costs were 12 to 13 times higher (€ 24.7 d/kg and € 33.0 d/kg of evaporated water) than that of the protective sheet dryer. The profit was three to five times higher than that of the leaves (€ 0.7/kg and € 1/kg of evaporated water). Finally the chamber solar dryer, an unusual case of significant investment 20 times that of the protective sheet dryer (€ 50.4 d/kg of evaporated water) also gave a profit more than 20 times higher than that of the protective sheet dryer (€ 4.2 d/kg of evaporated water). It turned out that higher investment in the purchase of the dryer when adapted to a need, made it possible to achieve greater benefits. However, the difficulties of access to credit limited investment capacity.

4. Conclusion

This study presented a critical analysis of the dryers used in sub-Saharan Africa for tropical agricultural product drying based on an investigation and survey on the ground in Togo, Benin and Burkina Faso.

To characterize the special range of dryers surveyed in this study, first a review of the characteristic criteria given by existing literature for dryer classification was carried out. The parameters obtained by this review for dryers used in industrialized countries were not all adequate or sufficient for characterizing and especially for differentiating between the dryers used in the field. The work provided some other new criteria. This made it possible to take into account the geographical area, the types of users, their level of organization, the availability of materials, the availability and cost of energy, the available space in the field, the advantages and disadvantages expressed by users, the targeted markets and the ratio of investment to evaporative flow. All the criteria, from the literature and from this study, were grouped in five classes: dryer specifications, specifications of the products, energy and mass balance aspects, specifications of the surrounding environment and lastly, economic aspects.

All these criteria enabled us to characterize the existing and long-standing inventoried dryers.

The results of the survey showed that the dryers were different from those proposed in the literature. Most of the dryers found in the field and also studied beforehand were indirect solar dryers, but they did not satisfy the users because of their low capacity and over-long drying time.

Only a small variety of dryer types was actually used. This contrasted with the large number of dryers presented in existing literature, mainly dryers with solar collectors for such climatic zones. The number of uses of a given dryer was not correlated to the number of its corresponding research studies. All the dryers were grouped in 10 representative types (classes). The dryers used in the field were mostly traditional dryers exposed to the sun, direct and indirect solar dryers, very few hybrid dryers, and two kinds of gas dryers. The most widespread dryers, and those renewed by the users themselves, were traditional systems using direct exposure to the sun and the Atesta gas dryers without solar energy.

In order to compare several real drying situations with each other in this paper, rather than comparing drying rates which concern laboratory dryer studies, the field context was taken into account with its reality and the criteria used to compare the dryers were the dryer mass capacity, the drying time, the treated product

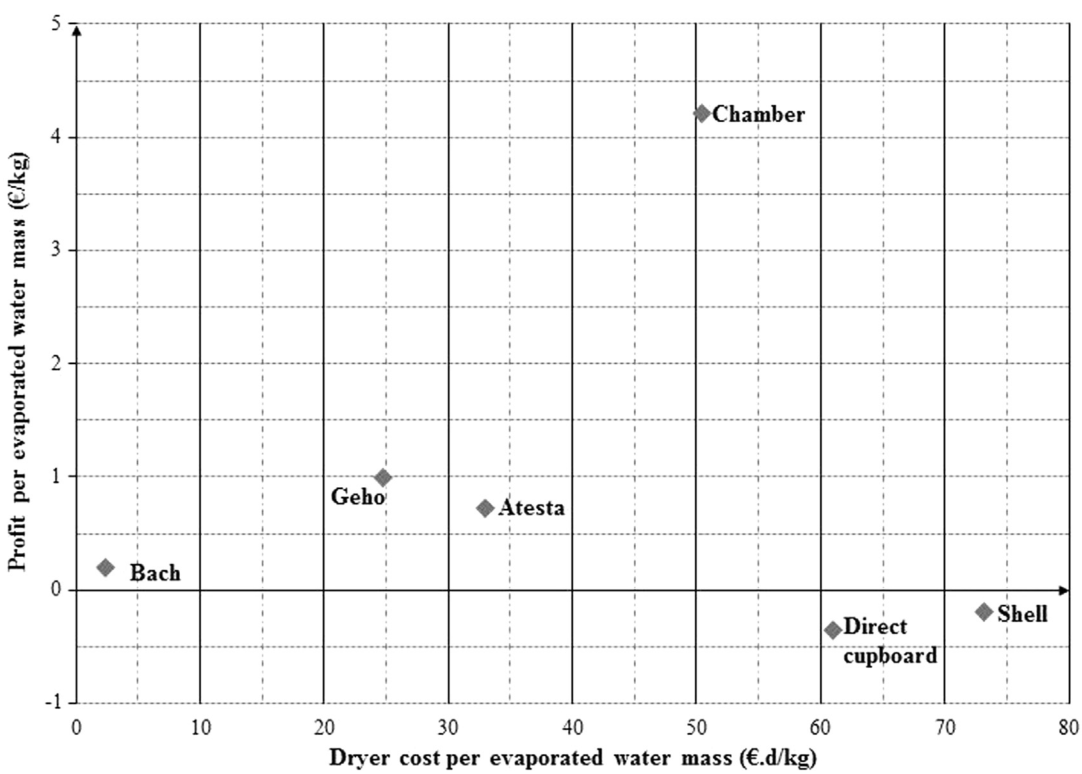


Fig. 4. Thermal and economic classification of the six analyzed dryers.

flow and the efficiency of the dryer. Efficiency was defined by the ratio of the energy collected by the described dryer configuration to the energy needed to evaporate water from the treated products during a cycle. Another point was revealed by this survey: a higher temperature than those found in the literature was often used during the first drying phase. But the users decreased the air temperature after some hours. Their know-how corresponded to physical phenomena: during the first drying period, the product surface temperature is at the wet bulb temperature of the air, which is lower than the air temperature. Given their know-how, they know at what time they need to decrease the air temperature.

This review brought out the dissatisfaction of the users and their needs, and revealed that the acquisition and development of the dryers were greatly influenced by social, economic and physical criteria such as:

– social criteria such as possible delivery and possible outlets for the products, and proximity of the manufacturers;
– the profitability of the dryers, which varied depending on the type of product, the dryer, and the end use for the dried products. This was evaluated from the profit derived by users from the dryer expressed in € per kg of evaporated water. The renewal of a dryer was therefore mostly governed by the value of that profit;
– the capacity of the current dryers which was often too small for the products processed.

The analysis of existing dryers enabled a socio-economic and energy analysis to be carried out, using the criteria proposed and calculating their values from the gathered data. A thermo-economic analysis was carried out on six characteristic dryers, taken from the inventoried dryers, in a real situation. It showed that for the most widely used dryers (solar and gas type dryers), the drying cost $C_{dry,w}$ was € 0.01/kg for direct exposure (sun drying) and € 0.07/kg for the gas dryer (Atesta); this amounted to 7% and 8% of the achieved profit, respectively (Table 14). The acquisition of other dryers was aided by donations or grants.

It turned out from this study that energetic efficiency and the criteria found in the literature were not sufficient for identifying or developing a dryer adapted to needs in the sub-Saharan area. Moreover, it also appeared important to take into account the type of product to be dried, the profitability of the activity, the end use and outlets for the product and the technical, social and climatic environment. An application of this study might be helpful to users by developing a support tool for selecting dryers taking into account these various constraints.

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